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THE EMP RESPONSE OF A SYSTEM OF UNCOUPLED, INTERCONNECTED CABLE--ETC(U)

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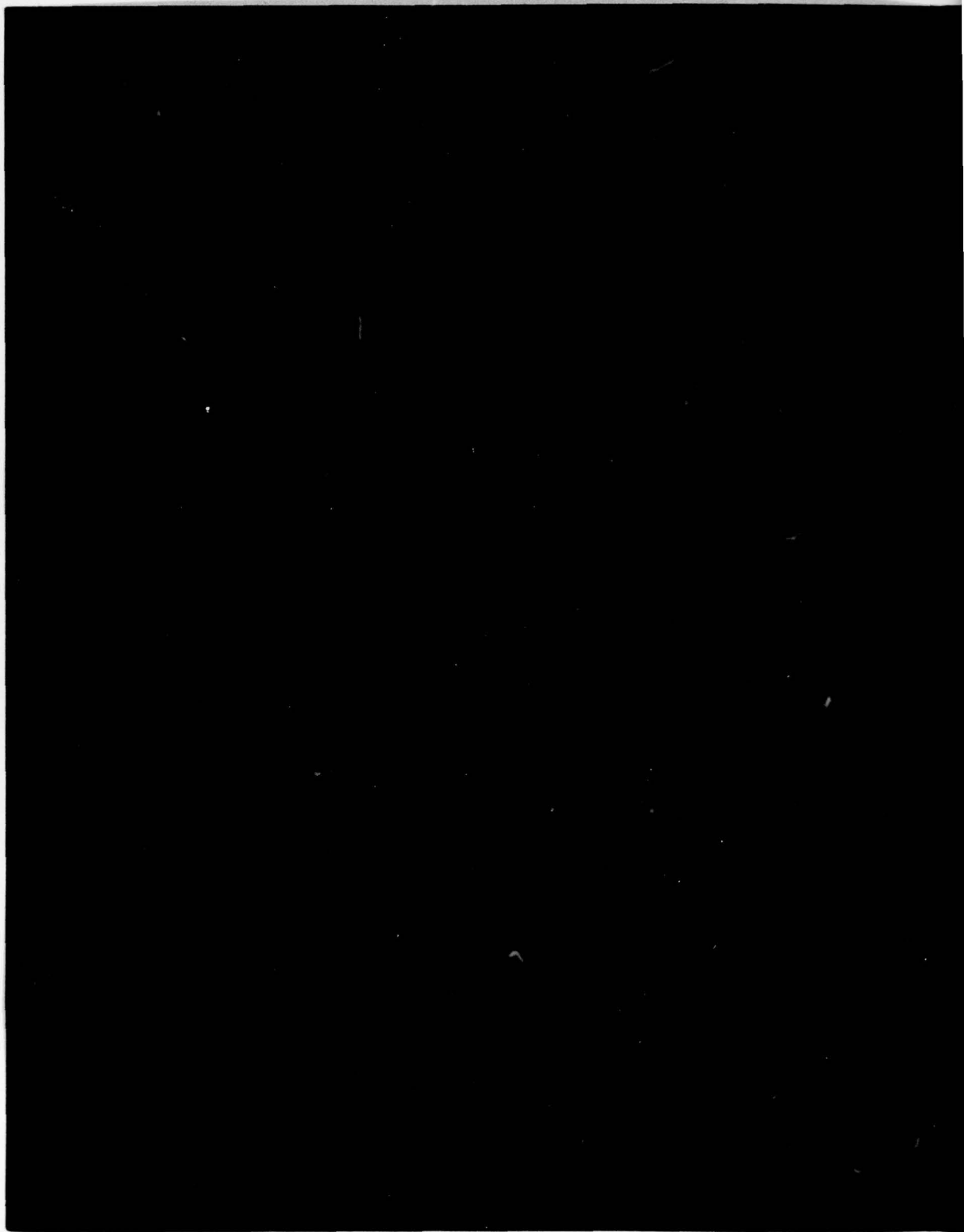


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The magnitudes of the experimental and calculated responses for the three conditions ($V_2 = 0$, $V_1 = 0$, $V_1 = V_2$) are shown in figures 5, 6, and 7. As expected, the agreement right at the resonance points is poor because of the lossless line assumption. However, the comparisons of experimental and calculated results over the remainder of the curves seem to be more than sufficient to validate the applicability of superposition.

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| 19. ABSTRACT (Continue on reverse side if necessary and identify by block number) An approximate analytical technique is developed for the electromagnetic pulse (EMP) response of a complex system of cables deployed over a real earth. The technique involves an existing transmission-line solution for the EMP response of a cable which is extended to a system of interconnected but uncoupled cables by the principle of superposition. The complete response of one particular cable is found by replacing all the other cables connected to it with equivalent Thevenin sources. The response of | | |

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the cable due to the EMP and the equivalent sources are then summed. The equivalent Thevenin sources are developed from the existing transmission-line solution for the EMP response of a single cable. Experimental verification of the applicability of the superposition principle to transmission lines is also given.

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1. INTRODUCTION

In analyzing the EMP response of complex systems, the analyst is usually forced to make simplifying assumptions about the system and its electrical characteristics. If the interaction and coupling problem of interest is an exterior cable (one exposed directly to the incident EMP) it is normally necessary to assume that no other cables associated with the system are excited by the EMP, that the cable has a constant height above ground (or below), and that the cable is straight with terminations appearing only at each end. In many instances, these necessary assumptions are not unduly restrictive and some worst-case "hand-waving" can be done to justify making them. However, these justifications become extremely difficult for complex systems which have many cables associated with them.

This paper investigates a technique for extending the applicability of existing single-cable coupling codes to complex networks of uncoupled cables. The technique uses the property of superposition to account for the effects of having an arbitrary group of cables connected together. The solution presented here is limited to the response of a cable which has an arbitrary number of other cables attached to its ends as shown in figure 1. No loops of cables are permitted. The

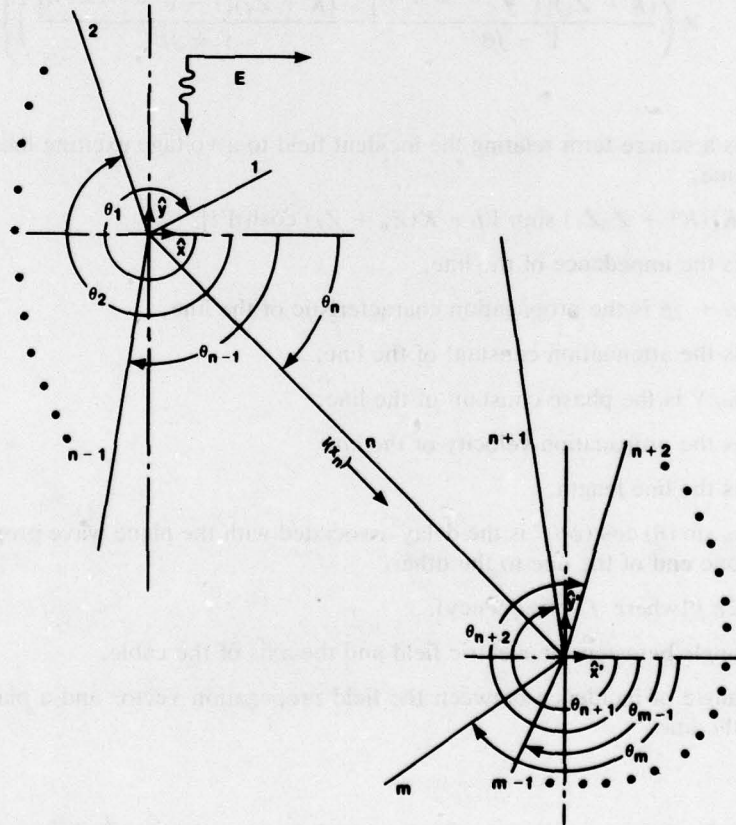


Figure 1. A system of m connected, uncoupled cables excited by an electric field E propagating in the Y direction.

extension of this technique to include loops would require a two-port distributed system representation of all the cables involved in the loop; this representation does not appear to have a compact solution at this time. The present technique is being used to modify the transmission-line coupling-code program FREFLD and the results of this effort will be reported on in a future report.

2. APPROACH

If one conducted a review of the various frequency-domain solutions for the current response of a two-wire transmission line excited by a horizontally polarized plane wave, most of these solutions would be similar to the equation¹

$$i(x) = \frac{E(\omega)}{2D} \left\{ [K \cosh \Gamma(l-x) + Z_l \sinh \Gamma(l-x)] \times \left(\frac{(K - Z_0)[1 - e^{-(\Gamma + j\beta')x}]}{\Gamma + j\beta'} - \frac{(K + Z_0)[1 - e^{-(\Gamma - j\beta')x}]}{\Gamma - j\beta'} \right) + e^{-j\beta'x} (K \cosh \Gamma x + Z_0 \sinh \Gamma x) \times \left(\frac{(K - Z_l)[1 - e^{-(\Gamma - j\beta')(x-l)}]}{\Gamma - j\beta'} - \frac{(K + Z_l)[1 - e^{-(\Gamma + j\beta')(x-l)}]}{\Gamma + j\beta'} \right) \right\} \quad (1)$$

where

$E(\omega)$ is a source term relating the incident field to a voltage exciting the transmission line,

$$D = K[(K^2 + Z_0 Z_l) \sinh \Gamma l + K(Z_0 + Z_l) \cosh \Gamma l],$$

K is the impedance of the line,

$\Gamma = \alpha + j\beta$ is the propagation characteristic of the line,

α is the attenuation constant of the line,

$\beta = \omega/V$ is the phase constant of the line,

V is the propagation velocity of the line,

l is the line length,

$\beta' = \omega \sin(\theta) \cos(\psi)/C$ is the delay associated with the plane wave propagating from one end of the line to the other,

$\omega = 2\pi f$ (where f is frequency),

θ = angle between the electric field and the axis of the cable,

ψ = angle of incidence between the field propagation vector and a plane normal to the line,

¹ R. F. Gray, Nuclear Electromagnetic Pulse Simulation by Point-Source Injection Techniques for Shielded and Unshielded Penetrations, Harry Diamond Laboratories, HDL-TR-1737 (December 1975).

c = speed of light,

x = point at which the current is calculated,

Z_0 = termination at $x = 0$, and

Z_l = termination at $x = l$.

The geometry used is shown in figure 2. This solution was developed for a wire or cable over a ground plane as shown, but the geometry only affects the source term $E(\omega)$ and not the rest of the equation. The solution for excitation by a vertically polarized plane wave has a form similar to that given here; the only differences are in the trigonometric terms and the grouping of terms in the numerator. Therefore, it will be stated, but not proved, that the technique developed here can be equally applicable for vertical and horizontal polarizations.

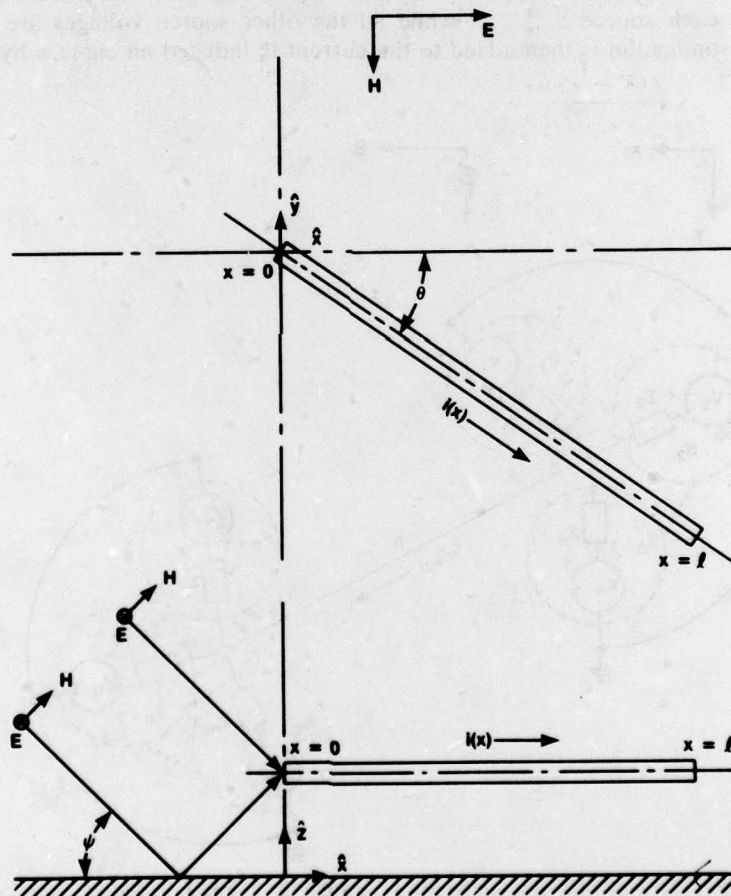


Figure 2. A conductor illuminated by a horizontally polarized wave.

In order to solve the coupling problem shown in figure 1, we first assume that each of the $m - 1$ cables connecting to cable n can be represented by its own equivalent source, $S_k |_{k=1, m}$ which is either a current or a voltage source, as shown in figure 3. Now, if the equivalent sources, S_k , exist and the only interaction between the cables is at $x = 0$ or $x = l$ but not both, then it should be possible to develop a systematic approach to solve for the current of interest, $i_n(x)$, at any point x , using the principal of superposition. It may be possible to account for the interaction between the cables by introducing additional equivalent source terms. There would also be an effect on the cable impedance if there is an interaction between cables over their length. In this report, it is always assumed that the areas of interaction between cables are small compared with the areas of noninteraction. This limitation does not appear to be overly restrictive, since a great many configurations are not in conflict with it. However, this restriction may have to be reevaluated after more work is done using this approximation.

We will assume for simplicity that all the sources, S_k , are voltage sources; however, this assumption does not mean a loss in generality, because the two equivalent representations are interrelatable. The desired current $i_n(x)$ can be found by summing up the current response, i_k^n , of the cable n to each source $S_k |_{k=1, m}$, while all the other source voltages are set to zero, $V_j = 0 |_{j=1, m; j \neq k}$; this summation is then added to the current i_n^n induced on cable n by the incident

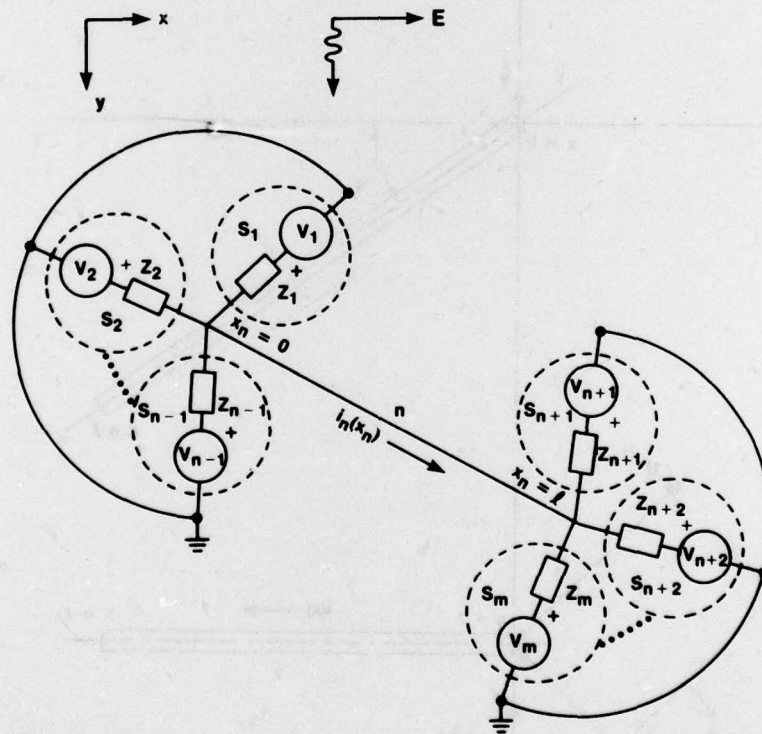


Figure 3. Cable n excited by the electric field E and by $m - 1$ independent equivalent sources, $S_k (k = 1, m; k \neq n)$, attached at its ends ($x_n = 0, l$).

field, E , as given by equation (1). Therefore, the current anywhere along cable n can be found from

$$\begin{aligned}
 i_n(x) &= \sum_{k=1}^{n-1} i_k^n \Big|_{\substack{V_j=0 \\ j \neq k, n}} + i_n^n \Big|_{\substack{V_j=0 \\ j=1, m \\ j \neq n}} + \sum_{k=n+1}^m i_k^n \Big|_{\substack{V_j=0 \\ j \neq k, n}} \\
 &= \sum_{k=1}^{n-1} I_0(x) V_k^0 \Big|_{\substack{V_j=0 \\ j \neq k, n}} + i_n^n \Big|_{\substack{V_j=0 \\ j=1, m \\ j \neq n}} + \sum_{k=n+1}^m I_l(x) V_k^l \Big|_{\substack{V_j=0 \\ j \neq k, n}} \\
 &= I_0(x) \sum_{k=1}^{n-1} V_k^0 \Big|_{\substack{V_j=0 \\ j \neq n, k}} + i_n^n \Big|_{\substack{V_j=0 \\ j \neq n}} + I_l(x) \sum_{k=n+1}^m V_k^l \Big|_{\substack{V_j=0 \\ j \neq k, n}},
 \end{aligned} \tag{2}$$

where $I_0(x)$ and $I_l(x)$ are simply the current responses of a transmission line excited by an ideal voltage source of unit magnitude at each end, respectively ($x = 0$ or l). V_k^0 and V_k^l are ideal voltage source representations of the source voltages V_k for $x = 0$ and $x = l$. The difference between V_k and V_k^0 or V_k^l is that V_k is the open-circuit voltage at the end of cable k and V_k^0 or V_k^l is the voltage at the end of cable k while loaded by the other $n - 2$ or $m - n - 1$ cables. Therefore, $V_k^0|_{k=1, n-1}$ is related to $V_k|_{k=1, n-1}$ by a voltage divider network with the source impedance Z_k in series with the parallel impedance, Z_k^0 , of the other $n - 2$ source impedances:

$$V_k^0 = V_k \frac{Z_k^0}{Z_k + Z_k^0} \Big|_{k=1, n-1} \tag{3}$$

and

$$\frac{1}{Z_k^0} = \sum_{j=1}^{n-1} \frac{1}{Z_j} \Big|_{j \neq k} \tag{4}$$

Similarly, we have for V_k^l :

$$V_k^l = V_k \frac{Z_k^l}{Z_k + Z_k^l} \Big|_{k=n+1, m} \tag{5}$$

and

$$\frac{1}{Z_k^l} = \sum_{j=n+1}^m \frac{1}{Z_j} \Big|_{j \neq k} \tag{6}$$

The equations for $I_0(x)$ and $I_l(x)$ are¹

$$I_0(x) = K_n [K_n \cosh \Gamma_n (l_n - x) + Z_l^n \sinh \Gamma_n (l_n - x)] / D_n, \tag{7}$$

$$I_l(x) = -K_n (K_n \cosh \Gamma_n x + Z_0^n \sinh \Gamma_n x) / D_n, \tag{8}$$

¹ R. F. Gray, Nuclear Electromagnetic Pulse Simulation by Point-Source Injection Techniques for Shielded and Unshielded Penetrations, Harry Diamond Laboratories, HDL-TR-1737 (December 1975).

where

$$\frac{1}{Z_0^n} = \sum_{k=1}^{n-1} \frac{1}{Z_k} \quad (9)$$

$$\frac{1}{Z_l^n} = \sum_{k=n+1}^m \frac{1}{Z_k} \quad (10)$$

$$D_n = K_n[(K_n^2 + Z_0^n Z_l^n) \sinh \Gamma_n l_n + K_n(Z_0^n + Z_l^n) \cosh \Gamma_n l_n] \quad (11)$$

Therefore, all the variables in equation (2) have been defined by equations (3) through (11) except for the assumed equivalent source terms V_k and Z_k of the $m - 1$ decoupled cables. These terms are developed in the next section.

3. EQUIVALENT SOURCE OF AN EMP-EXCITED CABLE

The Thevenin equivalent source terms can be easily generated from equation (1) and the geometry given in figure 1. The voltage term V_k is simply the open-circuit voltage at the end of the k th cable multiplied by a phase shift term, $e^{j\omega\alpha_k}$, where α_k is a time delay which accounts for the position of the k th cable relative to the n th cable. The open-circuit voltage at the end ($x = 0, l$) of a cable can be found by multiplying the current $i(x)$ in equation (1) by the appropriate terminating impedance, Z_0 or Z_l , and then finding the limit as Z_0 or Z_l approaches infinity:

$$\begin{aligned} V_{oc}^0 &= \lim_{Z_0 \rightarrow \infty} -Z_0 i(0) \\ &= -\frac{E(\omega)[(K\Gamma - j\beta'Z_l) \sinh \Gamma l + (Z_l\Gamma - j\beta'K) \cosh \Gamma l - Z_l(\Gamma + j\beta')e^{-j\beta'l}]}{(\Gamma^2 + \beta'^2)[Z_l \sinh \Gamma l + K \cosh \Gamma l]} \quad (12) \end{aligned}$$

$$\begin{aligned} V_{oc}^l &= \lim_{Z_l \rightarrow \infty} Z_l i(l) \\ &= \frac{E(\omega)[(K\Gamma + j\beta'Z_0) \sinh \Gamma l + (Z_0\Gamma + j\beta'K) \cosh \Gamma l - Z_0(\Gamma - j\beta')e^{j\beta'l}]}{(\Gamma^2 + \beta'^2)[Z_0 \sinh \Gamma l + K \cosh \Gamma l]} \quad (13) \end{aligned}$$

It should be pointed out that the differences in equations (12) and (13) are due to the orientation of the cable with respect to the incident electric field. If the axis of the k th cable is parallel to the electric field ($\theta_k = 0$ deg) (see fig. 1) then $V_{oc}^0 = -V_{oc}^l$, assuming $Z_0 = Z_l$; either representation can be used to find V_k . However, for $\theta_k \neq 0$ deg, the proper choice of V_{oc}^0, V_{oc}^l must be made depending on the position of the cable in the electric field. If θ_k is between 0 and 180 deg, the wave will excite the $x_k = 0$ end of the line first; therefore, V_{oc}^0 is used in V_k . If θ_k is between 180 and 360 deg, V_{oc}^l is required because the wave hits the $x_k = l$ end of the line first. The equation for V_{oc}^l has an effective time shift for nonzero rotation ($180 < \theta_k < 360$) because of the phase constant β'_k . This time shift must be factored out, which is done by multiplying V_{oc}^l by $e^{+j\beta'_k l_k}$. If θ_n is nonzero, voltage terms $V_k|_{k>n}$ will have a time delay relative to those at $x_n = 0$; this delay is accounted for in the frequency domain by multiplying the voltage spectrum by $e^{-j\beta'_n l_n}$. The proper voltage terms, V_k , for either end of the n th cable and any cable rotation, θ_k , are given in table 1.

TABLE 1
Voltage Term, V_k , for Equivalent Source S_k

| Cable n connection | $0 \leq \theta_k \leq 180 \text{ deg}$ | $180 \text{ deg} < \theta_k < 360$ |
|-------------------------|--|---|
| $x = 0$ | V_{oc}^0 | $V_{oc}^l e^{j\beta' k l}$ |
| $x = l$ | $V_{oc}^0 e^{-j\beta' n l_n}$ | $V_{oc}^l e^{j(\beta' k l_k - \beta' n l_n)}$ |

The source impedance, Z_k , can be found by dividing the open-circuit voltage $V_{oc}|_{x=0,l}$ by the short-circuit current, $i_{sc}|_{x=0,l}$ which gives

$$Z_k^0 = \frac{V_{oc}^0}{-i_{sc}^0} = \frac{\lim_{Z_0 \rightarrow \infty} [Z_0 i(0)]}{\lim_{Z_0 \rightarrow 0} [i(0)]} = K \frac{K \sinh \Gamma l + Z_l \cosh \Gamma l}{Z_l \sinh \Gamma l + K \cosh \Gamma l}, \quad (14)$$

$$Z_k^l = \frac{V_{oc}^l}{i_{sc}^l} = \frac{\lim_{Z_l \rightarrow \infty} [Z_l i(l)]}{\lim_{Z_l \rightarrow 0} [i(l)]} = K \frac{K \sinh \Gamma l + Z_0 \cosh \Gamma l}{Z_0 \sinh \Gamma l + K \cosh \Gamma l}. \quad (15)$$

Equations (14) and (15) are simply the input impedances of transmission lines terminated in impedances Z_l and Z_0 , respectively. Obviously, if Z_0 is equal to Z_l then Z_k^0 and Z_k^l are equal.

This completes the development of the uncoupled transmission-line model. All the necessary parameters have been defined and the summation of currents on the cable of interest (cable n) is straightforward.

4. PENETRATION THROUGH AN IMPERFECT SHIELD

If cable n is actually a shielded cable, which is very likely in tactical Army systems, then the preceding solution for the current distribution on cable n can be used to calculate the internal response of the coaxial cable. The response of a coaxial cable to a single source at only one end is given elsewhere.¹ The solution for more than one source will simply result in a summation of responses similar to equation (2). The internal response of the coaxial cable due to the current coupled directly on cable n by the incident field will also have to be included. The solution for this current (also given elsewhere¹) is part of program FREFLD. Therefore, no additional development other than a proper summing technique is needed for the solution of the internal response of a coaxial cable with other cables attached to the ends of its shield.

5. EXPERIMENTAL VERIFICATION

A brief laboratory experiment was conducted to establish the validity of using superposition techniques with transmission lines. The accuracy of equation (1) has already been addressed.¹ The overall validation of the technique, including the assumption that the interaction between cables is negligible for many cases, will be investigated in future work.

¹ R. F. Gray, Nuclear Electromagnetic Pulse Simulation by Point-Source Injection Techniques for Shielded and Unshielded Penetrations, Harry Diamond Laboratories, HDL-TR-1737 (December 1975).

A network of three transmission lines was chosen, as shown in figure 4. Appropriate lengths of RG58 A/U coaxial cable were used for the three lines. The exterior shields of the cables insured that the uncoupled line approximation was accurate. The source voltages V_1 and V_2 were created by placing small resistances (~ 1 ohm) in series with the shields of cables 1 and 2 at the junction with cable 3. Two voltage sources were then attached across these resistors. The source impedance of the voltage sources was much greater than 1 ohm so that no loading of the sources occurred.

Three measurements were made using an HP 3042 automatic network analyzer system. This system consists of an HP 3570A network analyzer, and an HP 3330B synthesizer, controlled by an HP 9830 desktop calculator. The calculator performs the data reduction and output display as well as automating the measurements. All the measurements were made over a frequency range of 100 kHz to 13 MHz. First, the open-circuit voltage V_1^3 at the end of line three was measured relative to the source voltage V_1 with V_2 shut off. Then the voltage V_2^3 was measured with respect to the source voltage V_2 with V_1 shut off. Finally, the voltage V_{12}^3 was measured with respect to V_1 with $V_2 = V_1$.

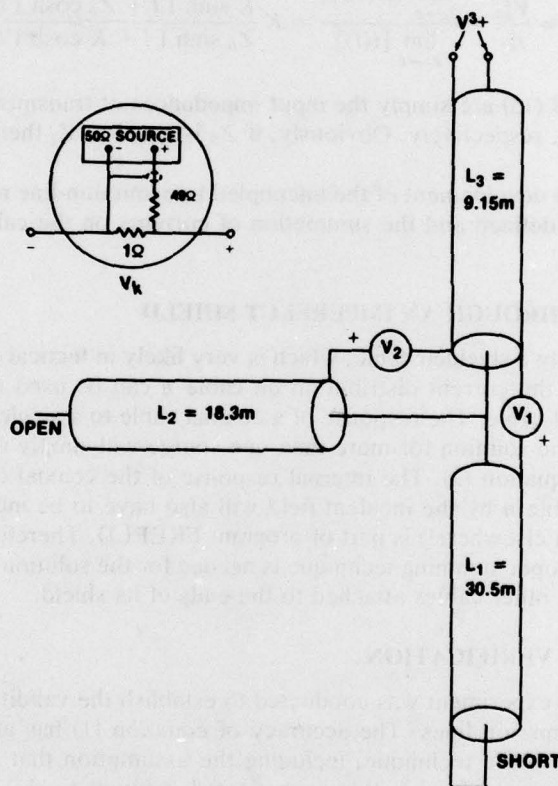


Figure 4. Experimental test setup for validating superposition principle for cable responses.

In order to simplify the comparison of measured and calculated results, we assumed that the transmission lines were lossless. This assumption should be relatively good except for right at the resonance points. The source impedances Z_1 and Z_2 are found from equation (14) to be

$$Z_1 = jK_0 \tan \beta l_1 = jK_0 \tan \frac{2\pi f l_1}{v} ,$$

$$Z_2 = -jK_0 \cot \beta l_2 = -jK_0 \cot \frac{2\pi f l_2}{v} ,$$

where $K_0 = 50$ ohms and $v = 2 \times 10^8$ m/s for RG 58 A/U coaxial cable. The voltage sources V_1 and V_2 are not needed since they were equal in the test and the measurements were normalized to the source voltage (i.e., V_3/V_1 or V_3/V_2 were the measured values). The terminating impedances for cable 3 are found from equations (9) and (10) to be

$$\begin{aligned} Z_3^0 &= 1 / \left(\sum_{k=1}^2 1/Z_k \right) = 1 / [1/(jK_0 \tan \beta l_1) + 1/(-jK_0 \cot \beta l_2)] \\ &= \frac{jZ_0 \tan \beta l_1}{1 - \tan \beta l_1 \tan \beta l_2} \end{aligned} \quad (16)$$

$$Z_3^1 = 1 / \left(\sum_{k=4}^{\infty} 1/Z_k \right) = Z_4 = \infty . \quad (17)$$

The ideal voltage sources V_1^0 and V_2^0 at $x = 0$ are found from equations (3) and (4):

$$V_1^0 = V_1 \frac{Z_2}{Z_1 + Z_2} = \frac{V_1}{1 - \tan \beta l_1 \tan \beta l_2} , \quad (18)$$

$$V_2^0 = V_2 \frac{Z_1}{Z_1 + Z_2} = \frac{V_2 \tan \beta l_1 \tan \beta l_2}{1 - \tan \beta l_1 \tan \beta l_2} , \quad (19)$$

and there are no source terms at $v = l$. The open-circuit voltage V_k^3 at $x = l$ due to either V_1 or V_2 is found from equation (9) by multiplying by Z_l and then taking the limit as Z_l approaches infinity:

$$V_k^3 = \lim_{Z_l \rightarrow \infty} Z_l I_0(l) = V_k^0 / (Z_3^0 \cos \beta l_3 + jK \sin \beta l_3) |_{k=1,2} . \quad (20)$$

Therefore, the lossless transmission line solutions for the first two measurements using only one source are found from equations (16), (18), (19), and (20) to be

$$V_1^3/V_1 = 1 / [\cos \beta l_3 (1 - \tan \beta l_1 \tan \beta l_2 - \tan \beta l_1 \tan \beta l_3)] , \quad (21)$$

$$V_2^3/V_2 = - \frac{\tan \beta l_1 \tan \beta l_2}{\cos \beta l_3 (1 - \tan \beta l_1 \tan \beta l_2 - \tan \beta l_1 \tan \beta l_3)} . \quad (22)$$

The third measurement with both sources exciting the system and with $V_1 = V_2$ is found from equation (2) to be the sum of equations (21) and (22).

The magnitudes of the experimental and calculated responses for the three conditions ($V_2 = 0$, $V_1 = 0$, $V_1 = V_2$) are shown in figures 5, 6, and 7. As expected, the agreement right at the resonance points is poor because of the lossless line assumption. However, the comparisons of experimental and calculated results over the remainder of the curves seem to be more than sufficient to validate the applicability of superposition.

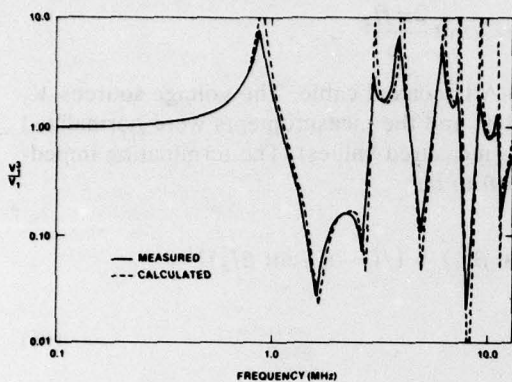


Figure 5. Ratio of V_1^3 to V_1 with $V_2 = 0$.

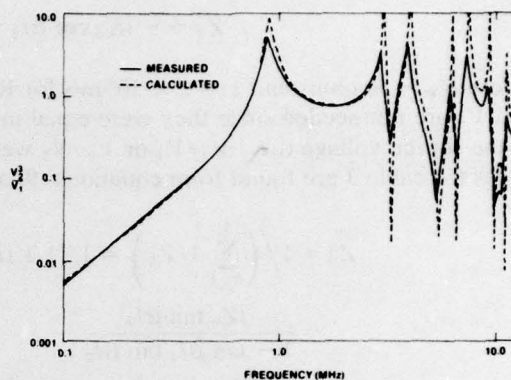


Figure 6. Ratio of V_2^3 to V_2 with $V_1 = 0$.

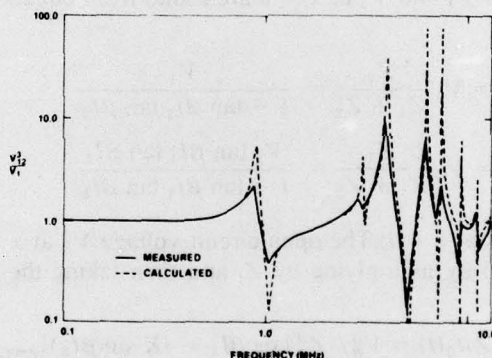


Figure 7. Ratio of V_{12}^3 to V_1 with $V_2 = V_1$.

6. CONCLUSIONS

An approximate solution has been developed for the EMP response of a coaxial cable with an arbitrary number of cables attached to its ends. Although the effect of some of the approximations (particularly, the noninteraction of the cables) remains to be determined, the basic approach of superposition of transmission-line responses has been verified experimentally. The technique outlined here will be used to develop a modified version of the computer program FREFLD. Once this new program is completed, the overall validity of the technique will be established.

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